Chapter 11

Ground-Based Narrow-Angle Astrometry

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11.1 Introduction

While atmospheric turbulence imposes severe limitations on the accuracy of wide-angle astrometric measurements performed from the ground, the limitations are far less severe for differential measurements over small fields. Performance in this regime is useful for a number of problems, including the search for extrasolar planets. As an indirect technique, astrometry measures the transverse reflex motion of the parent star for evidence of an unseen companion, analogous to radial-velocity measurements, which sense the velocity of the longitudinal reflex motion.

The astrometric signature of a Jupiter-Sun system, seen from a distance of 10 pc, has an amplitude of 500 μas (1 mas peak-to-peak), and establishes an upper limit on the accuracy of astrometric techniques to perform a useful search around nearby stars; single-measurement accuracies of < 100 μas are needed to search for lower-mass planets as well as to provide high-confidence detections. The amplitude of the astrometric signature can be written

$$\theta = \frac{m}{M}\frac{r}{L}, \tag{11.1}$$

where m and M are the planet and star masses, r is the orbital radius, and L is the distance of the system from the Earth. The signature can also be written

$$\theta = \frac{m}{M^{2/3}} \frac{P^{2/3}}{L}, \tag{11.2}$$

where P is the period of the system. Thus astrometry is most sensitive to planets with large orbital radii and long periods, and is complementary to the search space for radial-velocity measurements (Marcy and Butler, 1998).

11.2 Atmospheric Effects

The turbulent atmosphere introduces well-known spatial, temporal, and angular coherence losses parameterized by the coherence diameter r_0, coherence time τ_0, and the isoplanatic angle θ_0. For astrometry, we are most interested in how the astrometric error integrates down with time, which cannot be derived simply from the isoplanatic angle. It is intuitive that the astrometric error for a differential measurement should decrease with decreasing field as the atmosphere becomes common mode. The "sweet spot" for such measurement occurs with a long-baseline interferometer when the star separation is made smaller than the isokinetic angle B/h, where B is the interferometer baseline and h is an effective atmospheric height. In this regime, the error behavior is given by (Shao and Colavita, 1992)

$$\sigma_{\delta\theta} = 300 B^{-2/3} \theta t^{-1/2} \quad \text{arcsec}, \tag{11.3}$$

where we adopt a particular Mauna Kea atmospheric model. In this equation the error is given for integration time t in seconds and star separation θ in radians. This result assumes a strict infinite-outer-scale Kolmogorov atmosphere. Expected deviations from this behavior generally produce better performance. Thus, for a 20-arcsec star separation and a 100-m interferometer, the atmospheric error in one hour of integration time should be less than about 20 μas.

Much more detail on narrow-angle interferometric astrometry is presented by Shao and Colavita (1992).

11.3 Other Errors

For astrometry, an optical interferometer can be looked at geometrically; the problem is identical to the case of a radio interferometer (see Thompson *et al.* 1986). The delay x measured with the interferometer can be related to the interferometer baseline B and the star unit vector s as $x = B \cdot s$. Thus, measurements of delay in conjunction with knowledge of the baseline gives the angle of the star with respect to the baseline vector. The measured delay can be written

$$x = l + k^{-1}\phi, \tag{11.4}$$

where l is the laser-monitored internal delay, ϕ is the fringe phase, and k is the wavenumber of the interfering light.

We can capture most aspects of the measurement problem by reducing it to two dimensions and doing a small-angle approximation for sources near normal to the instrument, viz. $\theta \simeq x/B$. A trivial sensitivity analysis yields the error in the astrometric measurement to be

$$\delta\theta = \frac{\delta l}{B} + k^{-1}\frac{\delta\phi}{B} - \frac{\delta B}{B}\theta. \tag{11.5}$$

The first term incorporates systematic errors in measuring the internal delay; the second term incorporates errors in measuring the fringe phase, including photon and detector noise; the third term incorporates errors in measurement or knowledge of the interferometer baseline.

The long baselines achievable on the ground help reduce the requirements on systematic error control, which are challenging, but within the state of practice. For example, with a 100-m baseline, 10-μas systematic accuracy requires a 5-nm total length error. With differential measurements, certain systematic errors become common mode and do not affect accuracy. In addition, the astrometric measurement can be performed in a switching mode, reducing requirements on long-term thermal stability.

The dependence on θ in the third term of Equation 11.5 illustrates the difference in the requirements on baseline knowledge between wide- and narrow-angle astrometry. For wide-angle astrometry, $\theta \simeq 1$, leading to the intuitive result that the required fractional accuracy on the baseline is equal to the desired astrometric accuracy. However, for small fields, the requirement on baseline accuracy decreases: essentially, the baseline becomes more common mode to the differential measurement. For example, for a narrow-angle field of 20 arcsec, the requirements on the baseline are reduced by a factor of 10^4 compared with a wide-angle measurement.

The ability to measure the fringe phase places a limit on the achievable accuracy in a given integration time. The error $\delta\phi$ in a phase measurement can be written in terms of the signal-to-noise ratio SNR_ϕ,

$$\delta\phi = (\mathrm{SNR}_\phi)^{-1}, \tag{11.6}$$

where

$$\mathrm{SNR}_\phi^2 \simeq \frac{1}{2}\frac{N^2V^2}{N + B + M\sigma^2}, \tag{11.7}$$

where N is the total photon count, B is the total background and dark count, σ^2 is the read-noise variance, and M is the number of reads needed to make the phase measurement. The detection error shows up in the error expression, Equation 11.5, reduced by the baseline. Thus, long baselines help by reducing astrometric error for a given source brightness, or by improving sensitivity for a given accuracy.

11.4 Implementing a Narrow-Angle Measurement

Exploiting the tens-of-microarcsec astrometric accuracy possible with a ground-based narrow-angle astrometric measurement requires the ability to utilize nearby reference stars. One

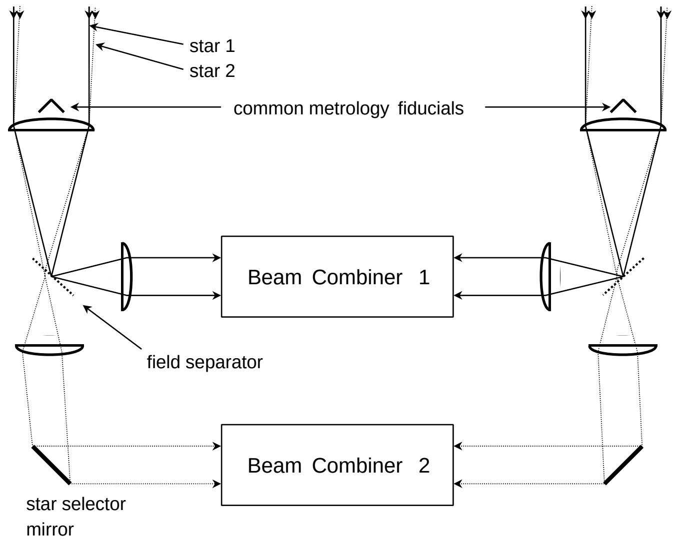

Figure 11.1: Dual-star architecture.

approach to this problem uses a dual-star architecture (Shao and Colavita, 1992), as shown in Figure 11.1. It consists of a long-baseline interferometer with dual beam trains. The light at each aperture forms an image of the field containing the target star and the astrometric reference. A dual-star feed separates the light from the two stars into separate beams which feed separate interferometer beam combiners. These beam combiners are referenced with laser metrology to a common fiducial at each collector. The two beam combiners make simultaneous measurements of the delays for the two stars.

Over a small field, reference stars will invariably be faint, and ordinarily would not be usable by the interferometer. However, searching for exoplanets is a unique problem in that the target star is nearby, and hence bright, and can serve as a phase reference. With phase referencing, the bright target star is used as a probe of the atmospheric turbulence within the isoplanatic patch of the target star. By compensating for the fringe motion of the target star with an optical delay line, the fringe motion of the faint astrometric reference star is frozen, allowing for long integration times which greatly increase sensitivity.

The radius of the isoplanatic patch increases with wavelength, and is 20–30 arcsec at 2.2 μm. With phase referencing and 1.5–2.0-m telescopes, astrometric references can be detected around most potential planetary targets.

Conducting a narrow-angle measurement with an architecture like that of Figure 11.1 involves two steps. The first step is wide-angle astrometry using known reference stars to solve for the interferometer baseline. As discussed above, the required baseline precision for a narrow-angle measurement is much less than for a wide-angle measurement, and the accuracies available from these wide-angle measurements provide sufficient accuracy. There are some subtleties regarding the wide-angle baseline as thus solved and the narrow-angle baseline applicable to the science measurement, and an auxiliary system may be required to tie these two baselines together.

The second step is to implement the measurement through chopping. In this approach, one interferometer beam combiner always tracks the target star. The other beam combiner switches repeatedly between the target star and the reference star. This "chopping" approach requires instrument stability only over the chop cycle. The use of even a low-resolution spectrometer in the fringe detector makes the ground-based measurements relatively insensitive to differential chromatic refraction.

In general, measurements on two orthogonal baselines are needed to detect systems with arbitrary inclinations. Measurements with respect to two reference stars are also desirable; with redundant measurements, astrometric noise in a reference star is, in most cases, separable from the desired (planetary) signature.

The Palomar Testbed Interferometer (Colavita *et al.*, 1999) was designed to demonstrate most aspects of narrow-angle astrometry for application to one of the key science modes of the Keck Interferometer (Colavita *et al.*, 1998; van Belle *et al.*, 1998). Recent results from PTI demonstrate a night-to-night repeatability of 100 μas on a bright visual binary (Boden *et al.*, 2000).

11.5 Conclusion

Long-baseline interferometers can exploit the behavior of the atmosphere over a small field to conduct high-accuracy measurements for applications such as exoplanet detection. The particular nature of this problem, i.e., that the target is bright and serves as a phase reference, allows cophasing the interferometer to obtain high sensitivity within the isoplanatic patch. While astrometry at the full accuracy allowed by the atmosphere is challenging, the long baselines achievable on the ground help moderate the effects of fringe-detection noise and systematic errors attributable to metrology and baseline knowledge.

Acknowledgments

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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